

SEMICONDUCTOR MATERIALS

Free electron theory:

In solids, electrons in outer most orbits of atoms determine its electrical properties. Electron theory is applicable to all solids, both metals and non metals. In addition, it explains the electrical, thermal and magnetic properties of solids. The structure and properties of solids are explained employing their electronic structure by the electron theory of solids.

It has been developed in three main stages:

1. Classical free electron theory
 2. Quantum Free Electron Theory.
 3. Zone Theory.
- **Classical free electron theory:** The first theory was developed by Drude & Lorentz in 1900. According to this theory, metal contains free electrons which are responsible for the electrical conductivity and metals obey the laws of classical mechanics.
 - **Quantum Free Electron Theory:** In 1928 Sommerfield developed the quantum free electron theory. According to Sommerfield, the free electrons move with a constant potential. This theory obeys quantum laws.
 - **Zone Theory:** Bloch introduced the band theory in 1928. According to this theory, free electrons move in a periodic potential provided by the lattice. This theory is also called “Band Theory of Solids”. It gives complete informational study of electrons.

Classical free electron theory:

Even though the classical free electron theory is the first theory developed to explain the electrical conduction of metals, it has many practical applications. The advantages and disadvantages of the classical free electron theory are as follows:

Advantages:

1. It explains the electrical conductivity and thermal conductivity of metals.
2. It verifies ohm's law.
3. It is used to explain the optical properties of metals.
4. Metal composed of atoms in which electrons revolve around the nucleus are many states available for occupation. If the density of states is zero, no states can be occupied at that energy level.
5. The valence electrons are freely moving about the whole volume of the metals like the molecules of perfect gas in a container
6. The free electrons moves in random directions and collide with either positive ions or other free electrons. Collision is independent of charges and is elastic in nature
7. The movements of free electrons obey the laws of classical kinetic theory of gases
8. Potential field remains constant throughout the lattice.
9. In metals, there are large numbers of free electrons moving freely within the metal i.e. the free electrons or valence electrons are free to move in the metal like gaseous molecules, because nuclei occupy only 15% metal space and the remaining 85% space is available for the electrons to move.

Drawbacks:

1. It fails to explain the electric specific heat and the specific heat capacity of metals.
2. It fails to explain superconducting properties of metals.
3. It fails to explain new phenomena like photoelectric effect, Compton effect, black – body radiation, etc.
4. It fails to explain Electrical conductivity (perfectly) of semiconductors or insulators.
5. The classical free electron model predicts the incorrect temperature dependence of σ . According to the classical free electron theory, $\sigma \propto T^{-1}$.
6. It fails to give a correct mathematical expression for thermal conductivity.
7. Ferromagnetism couldn't be explained by this theory.
8. Susceptibility has greater theoretical value than the experimental value.

Quantum free electron theory of metals:

Advantages:

1. All the electrons are not present in the ground state at 0 K, but the distribution obeys Pauli's exclusion principle. At 0 K, the highest energy level filled is called Fermi-level.
2. The potential remains constant throughout the lattice.
3. Collision of electrons with positive ion cores or other free electrons is independent of charges and is elastic in nature.
4. Energy levels are discrete.
5. It was successful to explain not only conductivity, but also thermionic emission paramagnetism, specific heat.

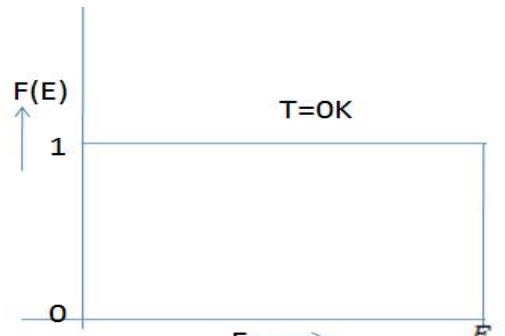
Drawbacks:

1. It fails to explain classification of solids as conductors, semiconductors and insulators.

Fermi level and Fermi energy:

The distribution of energy states in a semiconductor is explained by Fermi –Dirac statistics since it deals with the particles having half integral spin like electrons. Consider that the assembly of electrons as electron gas which behaves like a system of Fermi particles or fermions. The Fermions obeying Fermi –Dirac statistics i.e., Pouli, s exclusion principle.

Fermi energy: It is the energy of state at which the probability of electron occupation is $\frac{1}{2}$ at any temperature above 0K. It separates filled energy states and unfilled energy states. The highest energy level that can be occupied by an electron at 0 K is called Fermi energy level



Fermi level: It is a level at which the electron probability is $\frac{1}{2}$ at any temp above 0K (or) always it is 1 or 0 at 0K.

Therefore, the probability function $F(E)$ of an electron occupying an energy level E is given by,

Where E_F known as Fermi energy and it is constant for a system,
 K is the Boltzmann constant and T is the absolute temperature.

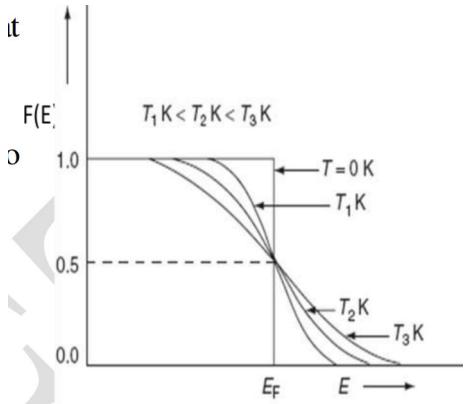
Case I : Probability of occupation at T=0K, and $E < E_F$

Therefore $F(E) = 1$, as per above, clearly indicates that at it

T=0K, the energy level below the Fermi energy level E_F is

fully occupied by electrons leaving the upper level vacant.

Therefore, there is 100% probability that the electrons to



Case II: Probability of occupation at $T = 0\text{K}$, and $E \geq E_S$

Then

i.e., all levels below E_F are completely filled and all levels above E_F are completely empty. As the temperature rises $F(E)$.

Case III: Probability of occupation at T= 0K, and $E = E_F$

$$F(E) = \frac{1}{1+e^0} = \frac{1}{1+1} = \frac{1}{2} = 0.5$$

The above condition states that, T=0K, there is a 50% probability for the electrons to occupy Fermi energy.

The probability function $F(E)$ lies between 0 and 1.

Hence there are three possible probabilities namely

$F(E) = 1$ 100% probability to occupy the energy level by electrons.

F(E) = 0 No probability to occupy the energy levels by electrons and hence ,it is empty.

$F(E) = 0.5$ 50% probability of finding the electron in the energy level.

Density of States (DOS):

The number of electrons per unit volume in an energy level at a given temperature is equal to the product of density of states (number of energy levels per unit volume) and Fermi Dirac distribution function (the probability to find an electron).

$$n_c = \int g(E) \times f(E) \, dE \dots \dots \dots \quad (1)$$

where n_c is the concentration of electrons, $g(E)$ is the density of states & $F(E)$ is the occupancy probability.

The number of energy states with a particular energy value E is depending on how many combinations of quantum numbers resulting in the same value n .

To calculate the number of energy states with all possible energies, we construct a sphere in 3D- space with ‘n’ as radius and every point (n_x , n_y and n_z) in the sphere represents an energy state.

As every integer represents one energy state, unit volume of this space contains exactly one state .Hence; the number of states in any volume is equal to the volume expressed in units of cubes of lattice parameters). Also $n^2 = n_x^2 + n_y^2 + n_z^2$

Consider a sphere of radius n and another sphere of radius $n+dn$ with the energy values are E and $(E+dE)$ respectively.

Therefore, the number of energy states available in the sphere of radius 'n' is

by considering one octant of the sphere

(Here, the number of states in a shell of thickness dn at a distance 'n' in coordinate system formed by n_x, n_y and n_z and will take only positive values ,in that sphere $\frac{1}{8}$ of the volume will satisfy this condition).

The number of energy states within a sphere of radius $(n+dn)$ is

$$\frac{1}{8} \left(\frac{4\pi}{3} \right) (n + dn)^3$$

Thus the number of energy states having energy values between E and $E+dE$ is given by

$$\begin{aligned} g(E)dE &= \frac{1}{8} \left(\frac{4\pi}{3} \right) (n + dn)^3 - \frac{1}{8} \left(\frac{4\pi}{3} \right) n^3 \\ &= \frac{1}{8} \left(\frac{4\pi}{3} \right) [(n + dn)^3 - n^3] \\ &= \frac{\pi}{6} (3n^2 dn) = \frac{\pi}{2} n^2 dn \end{aligned}$$

compared to ' dn ', ' dn^2 ' and ' dn^3 ' are very small .

Neglecting higher powers of dn

$$g(E)dE = \frac{\pi}{2} n^2 dn \dots \dots \dots (2)$$

The expression for n^{th} energy level can be written as ,

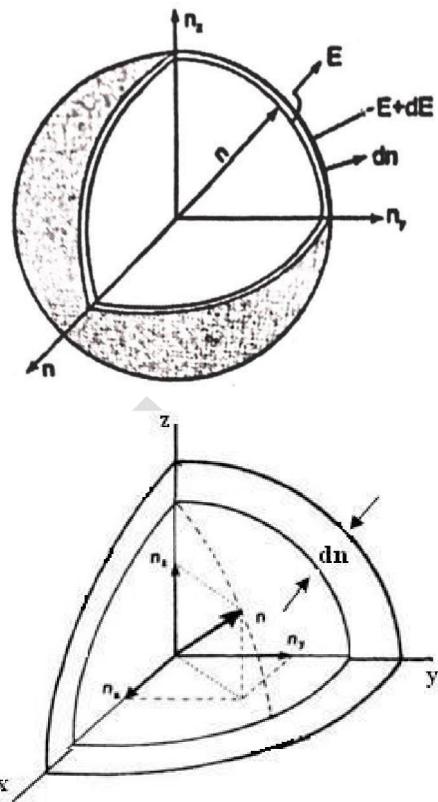
$$E = \frac{n^2 h^2}{8mL^2} \quad \text{or,} \quad n^2 = \frac{8mL^2 E}{h^2} \dots \dots \dots (3)$$

$$\Rightarrow n = \left(\frac{8mL^2 E}{h^2} \right)^{\frac{1}{2}} \dots \dots \dots (4)$$

Differentiating eq. (3):

$$2n dn = \frac{8mL^2}{h^2} dE \quad \Rightarrow \quad dn = \frac{1}{2n} \left(\frac{8mL^2}{h^2} \right) dE$$

\therefore by substituting $1/n$ value in dn ,



$$n = \frac{1}{2} \left(\frac{8mL^2}{h^2} \right)^{\frac{1}{2}} \frac{dE}{E^{\frac{1}{2}}} \dots \dots \dots (5)$$

Substitute n^2 and dn from eq. (3) and (5), we get

$$g(E)dE = \frac{\pi}{2} \left(\frac{8mL^2}{h^2} \right) E dE \times \frac{1}{2} \left(\frac{8mL^2}{h^2} \right)^{\frac{3}{2}} \frac{dE}{E^{1/2}}$$

$$g(E)dE = \frac{\pi}{4} \left(\frac{8mL^2}{h^2} \right)^{\frac{3}{2}} E^{\frac{1}{2}} dE \dots \dots \dots (6)$$

According to Pauli's Exclusion Principle, two electrons of opposite spin can occupy each energy state

Equation (6) should be multiplied by 2

$$g(E)dE = 2 \times \frac{\pi}{4} \left(\frac{8mL^2}{h^2} \right)^{\frac{3}{2}} E^{\frac{1}{2}} dE$$

After mathematical simplification, we get g

$$(E)dE = \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} E^{\frac{1}{2}} L^3 dE$$

The density of energy states $g(E) dE$ per unit volume is given by,

$$g(E)dE = \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} E^{\frac{1}{2}} dE \quad \because L^3 = 1$$

Bloch Theorem:

According to free electron model, a conduction electron in metal experiences constant potential. But in real crystal, there exists a periodic arrangement of positively charged ions through which the electrons move. As a consequence, the potential experienced by electrons is not constant but it varies with the periodicity of the lattice. In zone theory, as per Bloch, potential energy of electrons considered as varying potential with respect to lattice 'a'.

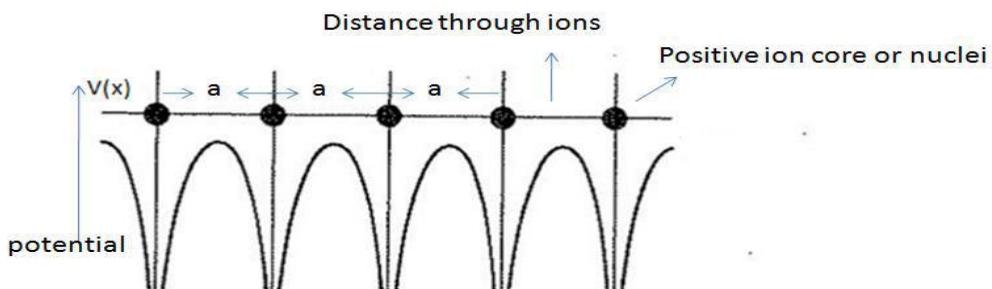


Fig: Variation of potential energy in a periodic lattice.

Let us examine one dimensional lattice as shown in figure. It consists of array of ionic cores along X-axis. A plot of potential V as a function of its position is shown in figure.

From graph:

At nuclei or positive ion cores, the potential energy of electron is minimum and in-between nuclei, the P.E. is considered as maximum w.r.to. Lattice constant 'a'.

This periodic potential $V(x)$ changes with the help of lattice constant a ,

$$V(x) = V(x + a) \quad ('a' \text{ is the periodicity of the lattice})$$

To solve, by considering Schrodinger's time independent wave equation in one dimension,

$$\frac{d^2\psi}{dx^2} + \frac{8\pi^2m}{\hbar^2} [E - V(x)]\psi = 0 \dots \dots \dots (1)$$

Bloch's 1D solution for Schrodinger wave equation (1) $\psi_k(x) = u_k(x)\exp(ikx) \dots \dots \dots (2)$

where $u_k(x) = u_k(x + a)$

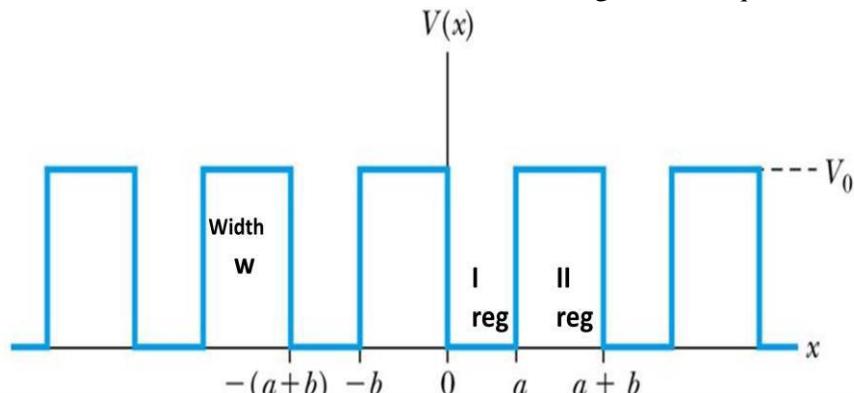
Here $u_k(x)$ -periodicity of crystal lattice, modulating function, k - propagation vector $= \frac{2\pi}{\lambda}$
 e^{ikx} is plane wave.

By applying eq.n (2) to eq.n (1), it is not easy to solve Schrodinger wave equation and Bloch cannot explains complete physical information about an e^- in periodic potential field. Then Kronig Penny model was adopted to explains the electrical properties of an e^- .

Kronig-Penney model:

Kronig-penny approximated the potentials of an e^- s inside the crystal in terms of the shapes of rectangular steps as shown, i.e. square wells is known as Kronig Penny model.

i.e. The periodic potential is taken in the form of rectangular one dimensional array of square well potentials and it is the best suited to solve Schrodinger wave equation.



It is assumed that the potential energy is zero when x lies between 0 and a , and is considered as I region. Potential energy is V_0 , when x lies between $-b$ and 0. And considered as II region.

Boundary conditions:

$V(x) = 0$, where x lies between $0 < x < a$ - I region. $V(x) =$

V_0 , where x lies between $-b < x < 0$ - II region.

This model explains many of the characteristic features of the behavior of electrons in a periodic lattice.

The wave function related to this model may be obtained by solving Schrodinger equations for the two regions,

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2} E\psi = 0, \text{ for } 0 < x < a \text{ with } V(x) = 0 \dots \dots \dots (1)$$

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2} (E - V_0)\psi = 0, \text{ for } -b < x < 0 \text{ with } V(x) = V_0 \dots \dots \dots (2)$$

Again,

$$\frac{d^2\psi}{dx^2} + \alpha^2 \psi = 0 \dots \dots \dots (3)$$

$$\text{where } \alpha^2 = \frac{2mE}{\hbar^2} \text{ and } \alpha = \frac{2\pi}{h} \sqrt{2mE}$$

$$\frac{d^2\psi}{dx^2} - \beta^2 \psi = 0 \dots \dots \dots (4)$$

$$\text{where } \beta^2 = \frac{2m}{\hbar^2} (V_0 - E)$$

The solution of these equations from Bloch theorem, $\psi_k(x) = u_k(x) \exp(ikx)$. From figure, square well potentials, if V_0 increases, the width of barrier 'w' decreases, if V_0 decreases the width of barrier w increases. But the (product) barrier strength $V_0 w$ remains constant.

To get this, differentiating above Schrodinger wave equations 3 & 4 w.r.to x, and by applying boundary conditions of x (w.r.to their corresponding Ψ), to known the values of constants A, B of region -I, C,D-for reg-II,we get mathematical expression (by simplification)

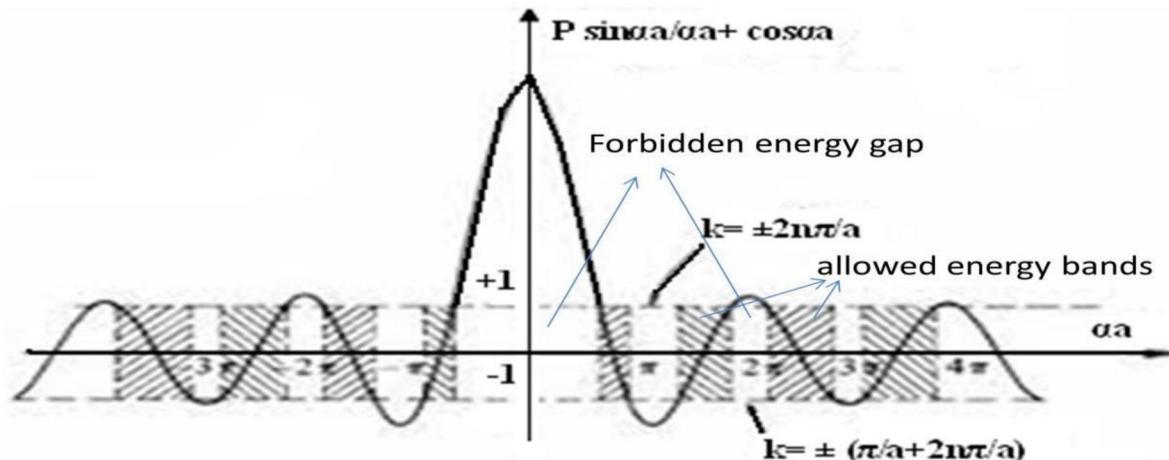
$$\cos ka = P \frac{\sin \alpha a}{\alpha a} + \cos \alpha a$$

where,

$$P = \frac{4\pi^2 m a}{\hbar^2} V_0 w \quad \text{and} \quad \alpha = \frac{2\pi}{h} \sqrt{2mE}$$

P-varying term, known as scattering power.

And ' $v_0 b$ ' is known as barrier strength.



Conclusions:

1. The L.H.S is a cosine term which varies between the limits -1 and +1, and hence the R.H.S also varies between these limits. It means energy is restricted within -1 to +1 only.
2. If the energy of e^- lies between -1 to +1, are called **allowed energy bands** and it is shown by shaded portion in energy spectrum. This means that ' αa ' can take only certain range of values belonging to allowed energy band.
3. As the value of αa increases, the width of the allowed energy bands also increases.
4. If energy of e^- s not lies between -1 to +1 are known as **forbidden energy bands** and it is decreases w.r.to increment of αa .
5. Thus, motion of e^- s. in a periodic lattice is characterized by the bands of allowed & forbidden energy levels.

Case 1:

1. $P \rightarrow \infty$

If $P \rightarrow \infty$, the allowed band reduces to a single (line) energy level, gives us steeper lines.

We have

$$\cos ka \left(\frac{\alpha a}{P} \right) = \sin \alpha a + \cos \alpha a \left(\frac{\alpha a}{P} \right)$$

$$P \rightarrow \infty, \frac{1}{\infty} = 0 \quad \text{then} \quad \sin \alpha a = 0$$

$$\sin \alpha a = \sin n\pi$$

$$\alpha a = n\pi$$

$$\alpha^2 a^2 = n^2 \pi^2$$

$$\alpha^2 = \frac{n^2 \pi^2}{a^2}$$

$$\frac{2mE}{\hbar^2} = \frac{n^2 \pi^2}{a^2}$$

$$E = \frac{n^2 \pi^2 \hbar^2}{2ma^2} = \frac{n^2 \pi^2 \hbar^2}{2ma^2 4\pi^2}$$

$$E = \frac{n^2 \hbar^2}{8ma^2}, \text{ here } a \text{ is lattice constant}$$

It means, it (zone theory) supports quantum free electron theory.

Case 2:

$P \rightarrow 0$, We have

$$\cos ka = P \frac{\sin \alpha a}{\alpha a} + \cos \alpha a$$

$$\alpha a = ka$$

$$\alpha = k$$

$$\alpha^2 = k^2$$

$$\frac{2mE}{\hbar^2} = \left(\frac{2\pi}{\lambda} \right)^2 = \frac{4\pi^2}{\lambda^2}$$

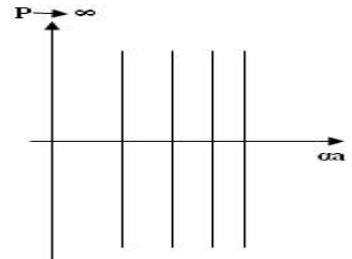
$$E = \frac{4\pi^2 \hbar^2}{2m\lambda^2}$$

$$E = \frac{4\pi^2 \hbar^2}{2m\lambda^2 4\pi^2}$$

$$E = \frac{1}{2} mv^2$$

It gives us kinetic energy of an electron. It means zone theory supports classical free electron theory at this situation electron completely free electron not bounded with allowed and forbidden gaps (and no energy level exists).

Thus by varying P from 0 to ∞ , we find that the completely free electron(s) becomes completely bound to Brillouin Zone.



Brillouin Zone OR E-K diagram:

The Brillouin zone are the boundaries that are marked by the values of wave vector k , in which electrons can have allowed energy values. These represent the allowed values of k of the electrons in 1D, 2D,&3D.

We have ,the energy of the electron in a constant potential box is,

$$E = \frac{n^2 h^2}{8ma^2} \dots \dots (1) \text{ where } a = \text{length of the box.}$$

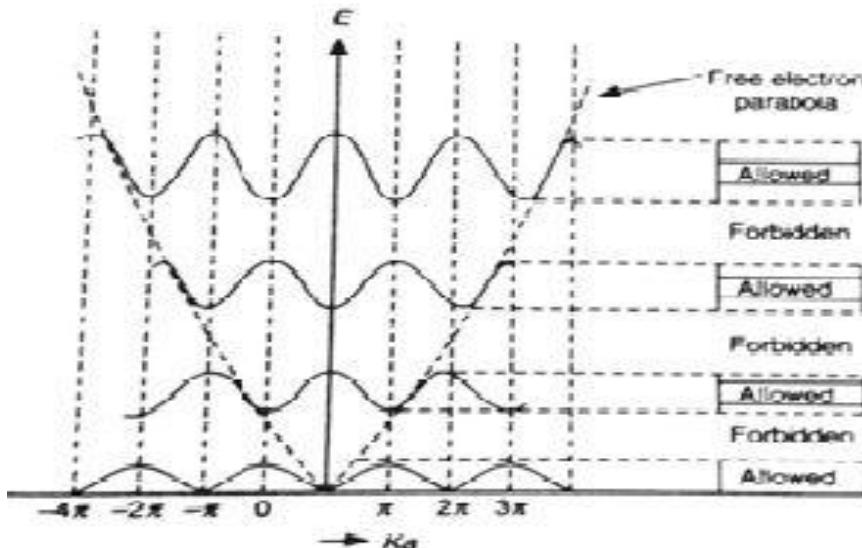
But,

$$k = \frac{n\pi}{a} \Rightarrow k^2 = \frac{n^2 \pi^2}{a^2}$$

$$\frac{n^2}{a^2} = \frac{k^2}{\pi^2} \dots \dots \dots (2)$$

Substitute eqn (2) in (1) ,we get $E = \frac{k^2 h^2}{8m\pi^2}$; $E \propto k^2$. It represents parabolic equation.

A graph is drawn between the total energy (E) and the wave vector k ,for various values of k . i.e. $k = \frac{n\pi}{a}$; $n = \pm 1, \pm 2, \pm 3, \dots \dots$



It is the energy spectrum of an electron moving in presence of a periodic potential field and is divided into allowed energy regions (allowed zones) or forbidden energy gaps (forbidden zones).

Allowed energy values lie in the region $k=-\pi/a$ to $=+\pi/a$. This zone is called the first Brillouin zone. After a break in the energy values, called forbidden energy band, we have another allowed zone spread from $k=-\pi/a$ to $-2\pi/a$ and $+\pi/a$ to $+2\pi/a$. This zone is called the second Brillouin zone. Similarly, higher Brillouin zones are formed

Concept of effective mass of electron:

When an electron in a periodic potential of lattice is accelerated by an known electric field or magnetic field, then the mass of the electron is called effective mass and is represented by m^* .

To explain, let us consider an electron of charge 'e' and mass 'm' moving inside a crystal lattice of electric field E.

Then by taking known expression $F=ma$, can be considered here as $F = m * a \dots \dots \dots (1)$

The acceleration $a = \frac{eE}{m}$ is not constant in the periodic lattice but varies due to the change in electronic mass.

If free electron under wave packet, the group velocity V_g corresponding to the particle's velocity can be written as

$$v_g = \frac{d\omega}{dk} = 2\pi \frac{dv}{dk} = \frac{2\pi}{h} \frac{dE}{dk} = \frac{1}{\hbar} \frac{dE}{dk} \dots \dots \dots (2) \text{ where } E = h\nu$$

The rate of change of velocity is known as

$$\text{Acceleration, } a = \frac{dv_g}{dt} = \frac{1}{\hbar} \frac{d^2E}{dk dt}$$

$$a = \frac{1}{\hbar} \frac{dE}{dt} \frac{dk}{dk} = \frac{1}{\hbar} \frac{d^2E}{dk^2} \frac{dk}{dt} \dots \dots \dots (3)$$

$$\text{From quantum mechanics relation, } p = \hbar k \dots \dots \dots (4)$$

$$\text{and } F = \frac{dp}{dt} \dots \dots \dots (5)$$

By differentiating eq (4) w.r.to t ,and by substituting eq(5)

$$\hbar \frac{dk}{dt} = \frac{dp}{dt} = F \Rightarrow \frac{dk}{dt} = \frac{F}{\hbar} \dots \dots \dots (6)$$

by substituting eq.(6) in eq (3),

$$\therefore a = \frac{1}{\hbar} \frac{d^2E}{dk^2} \frac{F}{\hbar}$$

By rearranging the above term and by comparing with eq.(1)

$$F = \left[\frac{\hbar^2}{\left(\frac{d^2E}{dk^2} \right)} \right] a$$

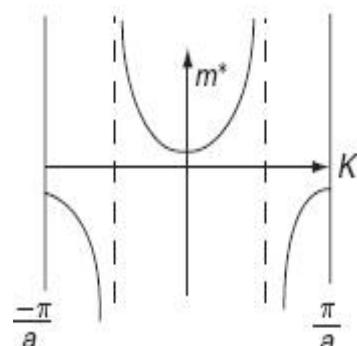
$$\therefore m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dk^2} \right)}$$

Is known as expression for m^* and it depends on E and K.

Variation of m^* with k:

The graph shows variation of m^* with k. Near k=0, effective mass approaches m. As the k value increases m^* increases, reaching its maximum value known as infinite effective mass.

Above the point of inflection, m^* is negative and as k tends to $\frac{\pi}{a}$, it decreases to a small negative value called negative effective mass in the lower region. The positively charged particle which can be located in the lower region called negative effective mass



Origin of energy band formation in Solids:

The band theory of solids explains the formation of energy bands and determines whether a solid is a conductor, semiconductor or insulator.

The existence of continuous bands of allowed energies can be understood starting with the atomic scale. The electrons of a single isolated atom occupy atomic orbitals, which form a discrete set of energy levels.

When two identical atoms are brought closer, the outermost orbits of these atoms overlap and interact. When the wave functions of the electrons of different atoms begin to overlap considerably, the energy levels corresponding to those wave functions split.

If more atoms are brought together more levels are formed and for a solid of N atoms, each of the energy levels of an atom splits into N energy levels. These energy levels are so close that they form an almost continuous band. The width of the band depends upon the degree of overlap of electrons of adjacent atoms and is largest for the outermost atomic electrons.

As a result of the finite width of the energy bands, gaps are essentially leftover between the bands called forbidden energy gap.

The electrons first occupy the lower energy levels (and are of no importance) then the electrons in the higher energy levels are of important to explain electrical properties of solids and these are called valence band and conduction band.

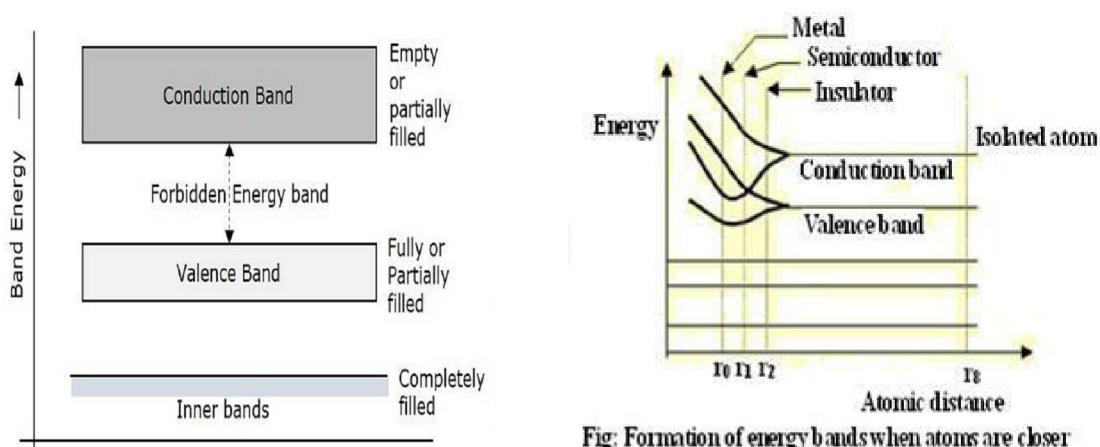


Fig: Formation of energy bands when atoms are closer

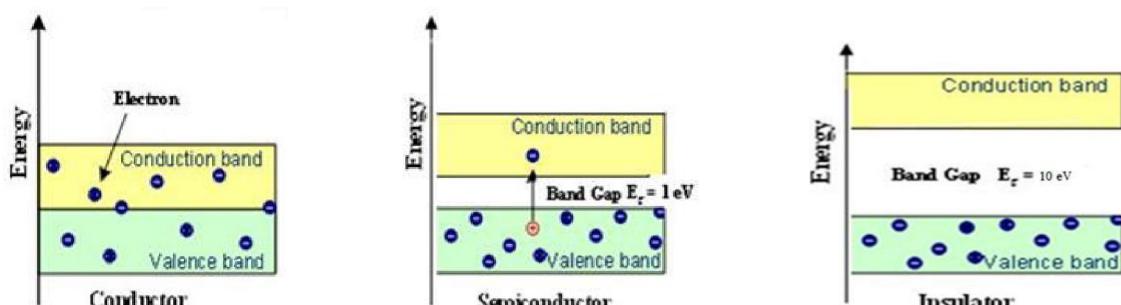
Valence band: A band occupied by valence electrons and is responsible for electrical, thermal and optical properties of solids and it is filled at 0K.

Conduction band: A band corresponding to outer most orbit is called conduction band and is the highest energy band and it is completely empty at 0K.

The **forbidden energy gap** between valence band conduction band is known as the energy band gap. By this solids are classified in to conductors, semiconductors and insulators.

Classification of solids into conductors , semiconductors & insulators:

Based on the energy band diagram materials or solids are classified as follows:



Conductors: In this kind of materials, there is no forbidden gap between the valence band and conduction band. It is observed that the valence band overlaps with the conduction band in metals as shown in figure. There are sufficient numbers of free electrons, available for electrical conduction and due to the overlapping of the two bands there is an easy transition

of electrons from one band to another band takes place, and there is no chance for the presence of holes. Resistivity of conductors is very small and it is very few milli ohm meters. ($\Omega \text{ m}$).

Examples: All metals (Na, Mg, Al, Cu, Ni Cu, Ag, Li, Ar etc)

Semiconductors:

In semiconductors, there is a band gap exists between the valence band and conduction band and it is very less and it is the order of -1 to 2 eV are known as semiconductors. It will conduct electricity partially at normal conditions. The electrical resistivity values are 0.5 to 10^3 ohm meter. Due to thermal vibrations within the solid, some electrons gain enough energy to overcome the band gap (or barrier) and behave as conduction electrons. Conductivity exists here due to electrons and holes.

Examples: Silicon, Germanium, Ga As.

Insulators:

In insulators, the width of forbidden energy gap between the valence band and conduction band is very large. Due to large energy gap, electrons cannot jump from V.B to C.B. Energy gap is of the order of ~ 10 eV and higher than semiconductors. Resistivity values of insulators are 10^7 to 10^{12} ohm-m. Electrons are tightly bound to the nucleus, no valence electrons are available.

Examples: Wood, rubber, glass.

SEMICONDUCTOR PHYSICS

SEMICONDUCTORS: The substances whose conductivity lies in between conductors and insulators are called as *semiconductors*.

Properties:

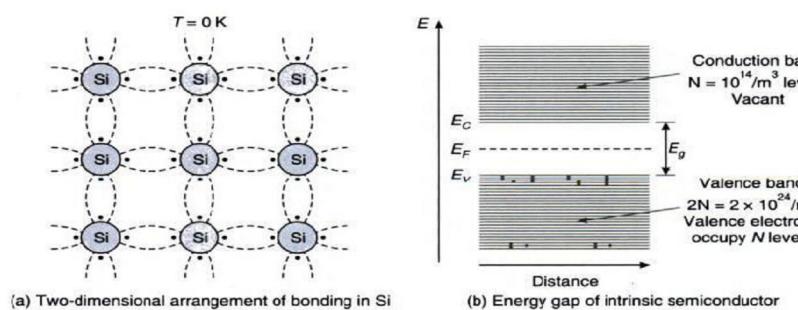
1. The conductivity of a semiconductors depends on it's temperature and it is increased with increase in temperature.
2. The energy gap of a semiconductor decreases with rise in temperature.
3. At 0 K a semiconductor becomes an insulator.
4. The absence of an electron in the VB of a semiconductor is called hole. Hole occur only in the VB. Or An empty electron state is called a hole.
5. Like electrons, the hole in the VB also conduct electricity in case of a semiconductor.
6. The electric current in a semiconductor is the sum of the currents due to electron and hole.
7. Hole is a positive charge carrier of current.

TYPES:

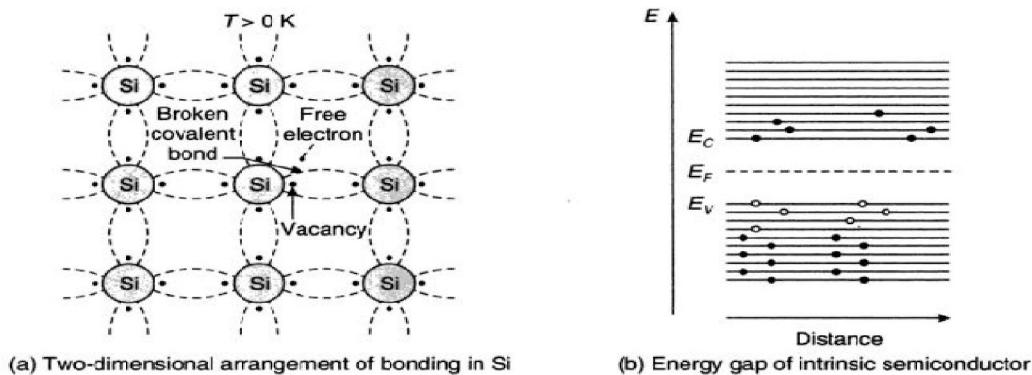
Depending on the relative concentration of holes and electrons the semiconductors are classified into two types.

1. Intrinsic Semiconductor
2. Extrinsic Semiconductor.

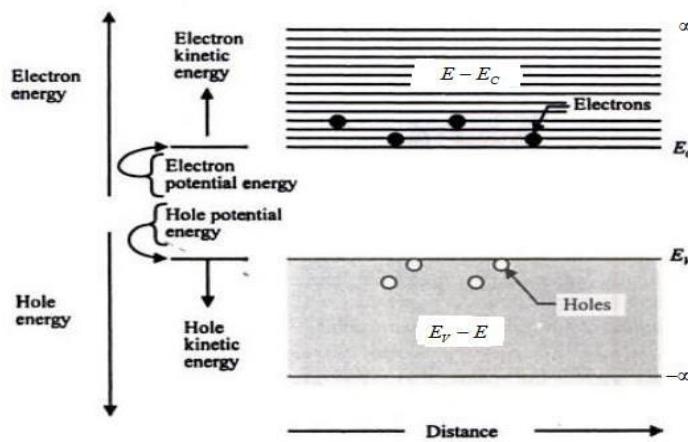
Intrinsic Semiconductor: The semiconductor which is pure and having the number of electrons in CB equal to number of holes in VB is called as *intrinsic semiconductor*. The examples of intrinsic semiconductor are pure silicon and pure germanium crystals. **The intrinsic semiconductors at 0 K** - The valence band is completely filled at 0 K and all the states in the conduction bands are vacant.



The intrinsic semiconductors at $T > 0\text{ K}$ - The valence band is not completely filled when $T > 0\text{ K}$ and some of the states in the conduction bands are occupied.



CARRIER CONCENTRATION IN AN INTRINSIC SEMICONDUCTOR:



Energies above the bottom edge E_c of the conduction band correspond to electron kinetic energy and energies below the top edge E_v of the valence band correspond to kinetic energy of holes.

The carrier concentration in an intrinsic semiconductor is determined by finding the concentration of electrons in the conduction band and the concentration of holes in the valence band and by applying the law of mass action.

At temperature above **0 K** two types of free charge carriers exist in a semiconductor, electrons in the conduction band and holes in the valence band. In general, it is taken that the conduction band is extended from E_c to $+\infty$ and the valence band is extended from $-\infty$ to E_v .

Concentration of electrons in the conduction band:

In a semiconductor, the conduction band is completely empty and the valence band is completely filled at **0 K**. If the temperature becomes greater than **0 K**, some of the electrons in valence band get excited into the conduction band.

Let us calculate the electrons available in the conduction band, when $T > 0 K$. The electron concentration in the conduction band can be obtained using the equation

$$n = \int_{\text{Bottom of CB}}^{\text{Top of CB}} (\text{density of states})(\text{fermi function})$$

$$n = \int_{E_c}^{\infty} g(E)F(E) dE \quad (1)$$

$$\text{Where } g(E) = \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} \quad \text{and} \quad F(E) = \frac{1}{1 + \exp(\frac{E - E_F}{KT})}$$

The electrons are moving in energy band but not in free space, so 'm' should be replaced by the effective mass(m_e^*). The term 'E' is replaced by $(E - E_c)$ because the bottom edge in the conduction band ' E_c ' is the potential energy of an electron at rest in the conduction band then $(E - E_c)$ represents the kinetic energy of the electron at high energy level.

$$n = \int_{E_c}^{\infty} \left[\frac{4\pi}{h^3} (2m_e^*)^{3/2} (E - E_c)^{1/2} \right] \left[\frac{1}{1 + \exp(\frac{E - E_F}{KT})} \right] dE \quad (2)$$

Since, $E > E_F$, the term $\exp\left(\frac{E-E_F}{KT}\right) > 1$, Therefore , neglecting 1. Eq. (2) can be written as

$$n = \int_{E_C}^{\infty} \left[\frac{4\pi}{h^3} (2m_e^*)^{3/2} (E - E_C)^{1/2} \right] \exp\left[-\left(\frac{E-E_F}{KT}\right)\right] dE \quad (3)$$

The above integral is solved by substituting $E - E_C = x$, then $dE = dx$, the lower limit of this integral becomes zero and the upper limit is ‘ ∞ ’. Eq. (3) becomes

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \int_0^{\infty} [(x)^{1/2}] \exp\left[-\left(\frac{x+E_C-E_F}{KT}\right)\right] dx \quad (4)$$

Equation (4) can be written as

$$\begin{aligned} n &= \frac{4\pi}{h^3} (2m_e^*)^{3/2} \int_0^{\infty} [(x)^{1/2}] \exp\left[-\left(\frac{E_C-E_F}{KT}\right)\right] \exp\left(\frac{-x}{KT}\right) dx \\ n &= \frac{4\pi}{h^3} (2m_e^*)^{3/2} \exp\left(\frac{E_F-E_C}{KT}\right) \int_0^{\infty} (x)^{1/2} \exp\left(\frac{-x}{KT}\right) dx \end{aligned} \quad (5)$$

The integral $\int_0^{\infty} (x)^{1/2} \exp\left(\frac{-x}{KT}\right) dx$ can be evaluated by substituting $\frac{x}{KT} = y$

Then $KT dy = dx$. There is no change in the upper and lower limit values.

$$\begin{aligned} \int_0^{\infty} (x)^{1/2} \exp\left(\frac{-x}{KT}\right) dx &= \int_0^{\infty} (yKT)^{1/2} \exp(-y) (KT) dy \\ &= (KT)^{3/2} \int_0^{\infty} (y)^{1/2} \exp(-y) dy \end{aligned} \quad (6)$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \exp\left(\frac{E_F-E_C}{KT}\right) (KT)^{3/2} \int_0^{\infty} (y)^{1/2} \exp(-y) dy \quad (7)$$

The integral $\int_0^{\infty} (y)^{1/2} \exp(-y) dy$ can be solved using the Gamma function.

The Gamma function is

$$\begin{aligned} \int_0^{\infty} y^{(n-1)} \exp(-y) dy &= \Gamma(n) \\ \int_0^{\infty} y^{(3/2-1)} \exp(-y) dy &= \Gamma\left(\frac{3}{2}\right) \\ &= \Gamma\left(\frac{1}{2} + 1\right) \\ &= \frac{1}{2} \Gamma\left(\frac{1}{2}\right) \quad \boxed{\Gamma(n+1) = n \Gamma(n)} \\ \boxed{\int_0^{\infty} y^{(3/2-1)} \exp(-y) dy = \frac{\sqrt{\pi}}{2}} \quad \boxed{\Gamma\left(\frac{1}{2}\right) = \sqrt{\pi}} \end{aligned}$$

Substituting $\int_0^{\infty} y^{(3/2-1)} \exp(-y) dy$ in equation (7)

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \exp\left(\frac{E_F-E_C}{KT}\right) (KT)^{3/2} \frac{\sqrt{\pi}}{2}$$

$$n = 2 \left[\frac{2\pi m_e^* KT}{h^2} \right]^{3/2} \exp\left(\frac{E_F-E_C}{KT}\right)$$

$$\boxed{n = N_C \exp\left(\frac{E_F-E_C}{KT}\right)}$$

$$\text{Where } N_C = 2 \left[\frac{2\pi m_e^* KT}{h^2} \right]^{3/2}$$

The above eq. gives the electron concentration in the conduction band.

Concentration of holes in the valence band:

In a semiconductor the conduction band is completely empty and valence band is completely filled at **0 K**. If the temperature becomes greater than **0 K**, some of the electrons in valence band gets excited into the conduction band.

Let us calculate the number of holes available in the valence band, when $T > 0 K$. The concentration of holes in the valence band is calculated by

$$p = \int_{\text{Bottom of VB}}^{\text{Top of VB}} (\text{density of stands})(\text{fermi function})$$

$$p = \int_{\text{Bottom of VB}}^{\text{Top of VB}} g(E) F_h(E) dE$$

We know that, the hole and electron occupation probability of the state of energy 'E' is always equal to 1.

It can be written as $F_e(E) + F_h(E) = 1$

The probability of occupancy of state by hole $F_h(E) = 1 - F_e(E)$

$$p = \int_{-\infty}^{E_V} g(E)[1 - F_e(E)] dE \quad (1)$$

Where $g(E) = \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2}$ and $F(E) = \frac{1}{1 + \exp(\frac{E-E_F}{KT})}$

$$1 - F_e(E) = 1 - \frac{1}{1 + \exp(\frac{E-E_F}{KT})}$$

$$= \frac{\exp(\frac{E-E_F}{KT})}{1 + \exp(\frac{E-E_F}{KT})}$$

Since, $E < E_F$, the term $\exp(\frac{E-E_F}{KT})$ in the denominator is less than 1. So, it is negligible. Therefore

$$1 - F_e(E) = \exp\left(-\frac{E-E_F}{KT}\right)$$

Substitute $g(E)$ and $1 - F_e(E)$ values in eq. (1)

$$p = \int_{-\infty}^{E_V} \left[\frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} \right] \left[\exp\left(-\frac{E-E_F}{KT}\right) \right] dE \quad (2)$$

The term E in eq. (2) is replaced by $(E_V - E)$ because E_V is the potential energy of a hole at rest. Then $(E_V - E)$ represents the kinetic energy of a hole at higher energy level. Note that the levels below the level E_F in the diagram are higher energy levels for holes. The hole is in energy band not in free space, so its mass is replaced by effective mass m_h^*

Then eq. (2) becomes

$$p = \int_{-\infty}^{E_V} \left[\frac{4\pi}{h^3} (2m_h^*)^{3/2} (E_V - E)^{1/2} \right] \left[\exp\left(-\frac{E-E_F}{KT}\right) \right] dE \quad (3)$$

$$p = \frac{4\pi}{h^3} (2m_h^*)^{3/2} \int_{-\infty}^{E_V} (E_V - E)^{1/2} \exp\left[-\left(\frac{E-E_F}{KT}\right)\right] dE \quad (4)$$

Let $E_V - E = x$, Then $-dE = dx$

The lower limit of this integral becomes ∞ and the upper limit is zero.

The integral (4) can be written as

$$p = \frac{4\pi}{h^3} (2m_h^*)^{3/2} \int_{-\infty}^0 (x)^{1/2} \exp\left[-\left(\frac{E_F - (E_V - x)}{KT}\right)\right] (-dx) \quad (5)$$

The above eq. (5) can be written as

$$\begin{aligned} p &= \frac{4\pi}{h^3} (2m_h^*)^{3/2} \int_0^\infty (x)^{1/2} \exp\left(\frac{E_V - E_F}{KT}\right) \exp\left(\frac{-x}{KT}\right) dx \\ p &= \frac{4\pi}{h^3} (2m_h^*)^{3/2} \exp\left(\frac{E_V - E_F}{KT}\right) \int_0^\infty (x)^{1/2} \exp\left(\frac{-x}{KT}\right) dx \end{aligned} \quad (6)$$

The integral $\int_0^\infty (x)^{1/2} \exp\left(\frac{-x}{KT}\right) dx$ can be evaluated by substituting $\frac{x}{KT} = y$

Then $KT dy = dx$. There is no change in the upper and lower limit values.

$$\begin{aligned} \text{i.e., } \int_0^\infty (x)^{1/2} \exp\left(\frac{-x}{KT}\right) dx &= \int_0^\infty (yKT)^{1/2} \exp(-y) KT dy \\ &= (KT)^{3/2} \int_0^\infty (y)^{1/2} \exp(-y) dy \end{aligned} \quad (7)$$

$$p = \frac{4\pi}{h^3} (2m_h^*)^{3/2} \exp\left(\frac{E_V - E_F}{KT}\right) (KT)^{3/2} \int_0^\infty (y)^{1/2} \exp(-y) dy \quad (8)$$

The above integral $\int_0^\infty (y)^{1/2} \exp(-y) dy$ can be solved using the Gamma functions

The Gamma function is

$$\begin{aligned} \int_0^\infty y^{(n-1)} \exp(-y) dy &= \Gamma(n) \\ \int_0^\infty y^{(3/2-1)} \exp(-y) dy &= \Gamma\left(\frac{3}{2}\right) \\ &= \Gamma\left(\frac{1}{2} + 1\right) \\ &= \frac{1}{2} \Gamma\left(\frac{1}{2}\right) & \boxed{\Gamma(n+1) = n \Gamma(n)} \\ \boxed{\int_0^\infty y^{(3/2-1)} \exp(-y) dy = \frac{\sqrt{\pi}}{2}} & & \boxed{\Gamma\left(\frac{1}{2}\right) = \sqrt{\pi}} \end{aligned}$$

Eq. (8) can be written as

$$\begin{aligned} p &= \frac{4\pi}{h^3} (2m_h^*)^{3/2} \exp\left(\frac{E_V - E_F}{KT}\right) (KT)^{3/2} \frac{\sqrt{\pi}}{2} \\ p &= 2 \left[\frac{2\pi m_h^* KT}{h^2} \right]^{3/2} \exp\left(\frac{E_V - E_F}{KT}\right) \\ \boxed{p = N_V \exp\left(\frac{E_V - E_F}{KT}\right)} & & \text{Where } N_V = 2 \left[\frac{2\pi m_h^* KT}{h^2} \right]^{3/2} \end{aligned}$$

The above equations gives the hole concentration in the valence band.

FERMI LEVEL IN INTRINSIC SEMICONDUCTOR

In an intrinsic semiconductor the concentration of in the valence band is equal to the concentration of electron in the conduction band.

$$\text{i.e., } n = p \quad (1)$$

Substituting n & p values in eq. (1)

$$N_C \exp\left(\frac{E_F - E_C}{KT}\right) = N_V \exp\left(\frac{E_V - E_F}{KT}\right)$$

$$\frac{N_C}{N_V} = \exp\left(\frac{E_V - E_F - E_F + E_C}{KT}\right)$$

$$\frac{N_C}{N_V} = \exp\left(\frac{E_V + E_C - 2E_F}{KT}\right)$$

Taking \log both sides we get,

$$\begin{aligned} \log\left(\frac{N_C}{N_V}\right) &= \frac{E_V + E_C - 2E_F}{KT} \\ E_V + E_C - 2E_F &= KT \log\left(\frac{N_C}{N_V}\right) \\ E_F &= \frac{E_V + E_C}{2} - \frac{KT}{2} \log\left(\frac{N_C}{N_V}\right) \end{aligned} \quad (2)$$

Now

$$\frac{N_C}{N_V} = \frac{\frac{2}{h^2} \left[2\pi m_e^* KT\right]^{3/2}}{\frac{2}{h^2} \left[2\pi m_h^* KT\right]^{3/2}} = \left(\frac{m_e^*}{m_h^*}\right)^{3/2} \quad (3)$$

From eq. (2) and eq. (3) we get

$$E_F = \frac{E_V + E_C}{2} - \frac{3KT}{4} \log\left(\frac{m_e^*}{m_h^*}\right) \quad (4)$$

The above eq. (4) gives the value of the Fermi level in intrinsic semiconductor.

As KT is small and the effective mass m_e^* and m_h^* do not usually differ much, the second term in the eq. (4) may be ignored.

If the effective mass of a free electron is assumed to be equal to the effective mass of a hole.

$$m_e^* = m_h^*$$

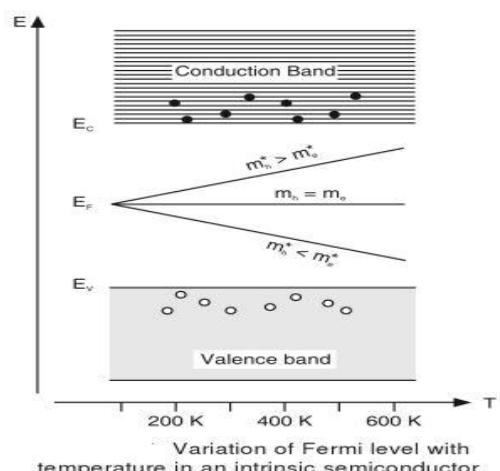
We get $E_F = \frac{E_V + E_C}{2}$

Thus, the Fermi level in a semiconductor lies at the center of the energy gap.

Variation Of Fermi Level With Temperature:

The Fermi level in an intrinsic semiconductor may be considered as independent of temperature as staying in the middle of the band gap.

- ✓ If $m_e^* > m_h^*$, E_F displaced downward to the top edge of the valence band.
- ✓ If $m_e^* < m_h^*$, with increase in temperature, the Fermi level gets displaced upward to the bottom edge of the conduction band.



EXTRINISIC SEMICONDUCTOR

When small quantities of selected impurities are added to an intrinsic semiconductor it becomes an extrinsic semiconductor. Depending upon the type of impurity extrinsic semiconductors are of two types, namely

1. P – type semiconductor.
2. N – type semiconductor.

Carrier Concentration:

The number of charge carriers present per unit volume of a semiconductor material is called **carrier concentration**.

Carrier Concentration In Extrinsic Semiconductor:

Consider an extrinsic semiconductor in which N_A acceptor atoms and N_D donor atoms are doped per unit volume of the semiconductor. Then at some room temperature **T K** the material contains n , p , N_A^- and N_D^+ .

The material will be electrically neutral if

$$n + N_A^- = p + N_D^+$$

Where $n \rightarrow$ concentration of free electrons.

$p \rightarrow$ concentration of holes.

$N_A^- \rightarrow$ concentration of acceptor ions per unit volume.

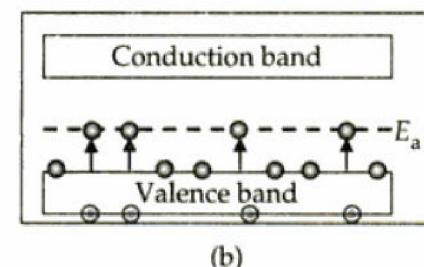
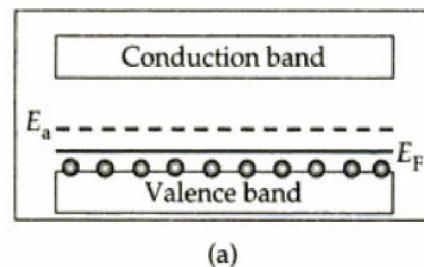
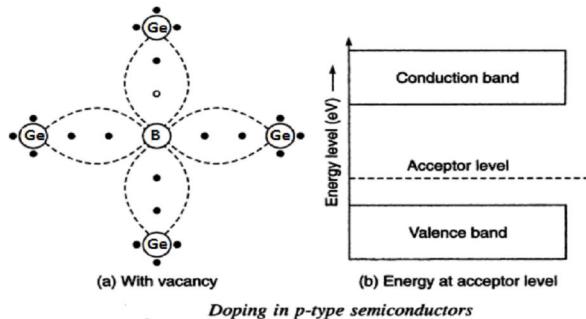
$N_D^+ \rightarrow$ concentration of donor ions per unit volume.

That is total concentration of negative charge in the semiconductor is equal to total concentration of positive charge in the semiconductor. The above equation is called **charge neutrality equation**.

P – TYPE SEMICONDUCTOR:

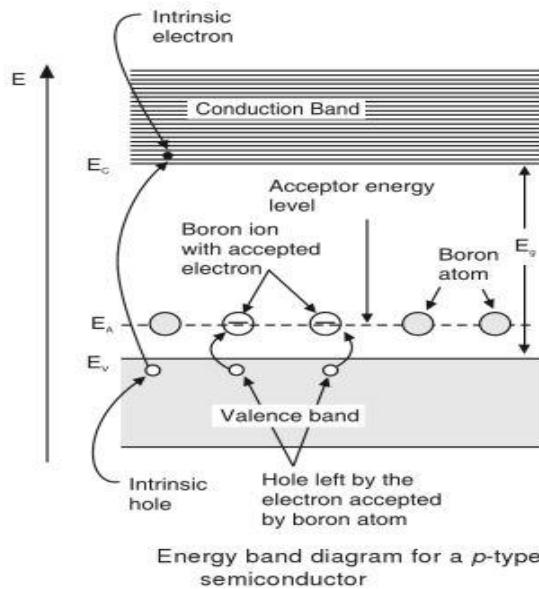
Generally pure semiconductor has 4 valence electrons and can form four covalent bonds. When a trivalent impure atoms (which have three valence electrons) like Gallium (**Ga**), **Al**, **In** or **Boron (B)** is added, these three valence electrons form three covalent bonds with, say **Ge** atom. But the 4th electron doesn't have a pair, so a '**hole**' exists. This means that it's ready to 'accept' an electron to fill the hole. Thus a small amount of trivalent impurity creates '**majority of holes**', which are positive, and are called as '**p-type semiconductor**' or '**Acceptors**'.

In a P - type semiconductor holes are majority current carriers and **electrons** are minority current carriers. In a P- type semiconductor, **the energy level of this acceptor impurity lies just above** the valence band. This energy level is called **acceptor level** and it is represented as E_A .



(a) $T = 0 \text{ K}$ and (b) $T > 0 \text{ K}$

CARRIER CONCENTRATION IN P-TYPE SEMICONDUCTOR:



In a *p* - type semiconductor, the doping concentration of acceptor atom is very large in comparison to the donor atoms, So N_D^+ is negligible. Further, in *p* - type semiconductors '*n*' is due to thermal generation only, so it will also be very small in comparison to N_A^- . Therefore, the charge neutrality equation for the *p* - type semiconductor as

$$P = N_A^- \quad (1)$$

Where

$p \rightarrow$ concentration of holes $N_A^- \rightarrow$
concentration of acceptor ions available in the acceptor level
or Ionised acceptor impurity.

The concentration of acceptor ion N_A^- is equal to the product of concentration of acceptor atoms N_A and the probability of finding an electron in acceptor level $f(E_A)$.

$$N_A^- = N_A f(E_A) \quad (2)$$

Where, N_A is acceptor concentration.

$f(E_A)$ is the probability that a quantum state is occupied by an electron in the acceptor level

From the Fermi dirac distribution function

$$f(E_A) = \frac{1}{1 + \exp\left(\frac{E_A - E_F}{KT}\right)} \quad (3)$$

Substituting eq. (3) in eq. (2) we get,

$$N_A^- = \frac{N_A}{1 + \exp\left(\frac{E_A - E_F}{KT}\right)} \quad (4)$$

Since, the acceptor level lies above the Fermi level, $E_A - E_F$ is positive.

Therefore, the term 1 is neglected, compared to $\exp\left(\frac{E_A - E_F}{KT}\right)$. Therefore,

Eq. (4) can be written as

$$N_A^- = N_A \exp\left[-\left(\frac{E_A - E_F}{KT}\right)\right] \quad (5),$$

Sub eq. (5) in eq. (1)

$$P = N_A \exp \left[-\left(\frac{E_A - E_F}{KT} \right) \right] \quad (6)$$

The concentration of holes in the valence band is

$$p = N_V \exp \left(\frac{E_V - E_F}{KT} \right) \quad (7)$$

Sub eq. (7) in eq. (6)

$$N_V \exp \left(\frac{E_V - E_F}{KT} \right) = N_A \exp \left[-\left(\frac{E_A - E_F}{KT} \right) \right]$$

$$\text{i.e., } \exp \left[\frac{E_V - E_F + E_A - E_F}{KT} \right] = \frac{N_A}{N_V}$$

In the above eq, taking log on both sides, we get,

$$E_F = \frac{E_V + E_A}{2} - \frac{KT}{2} \log \left(\frac{N_A}{N_V} \right) \quad (8)$$

Eq. (8) represents the Fermi level in a *p-type* semiconductor. At $T = 0 K$, Eq. (8) becomes

$$E_F = \frac{E_V + E_A}{2} \quad (9)$$

At $T = 0 K$, the Fermi energy level lies at the middle of the top of the VB and the acceptor level.

The concentration of hole in the valence band in an intrinsic semiconductor is

$$p = N_V \exp \left(\frac{E_V - E_F}{KT} \right) \quad (10)$$

Sub eq. (8) in eq. (10)

$$\begin{aligned} p &= N_V \exp \left[\frac{E_V}{KT} - \frac{E_V + E_A}{2KT} - \frac{KT}{2KT} \log \left(\frac{N_A}{N_V} \right) \right] \\ &= N_V \exp \left[\frac{E_V - E_A}{2KT} \right] \left(\frac{N_A}{N_V} \right)^{1/2} \\ &= (N_A N_V)^{1/2} \exp \left[\frac{E_V - E_A}{2KT} \right] \end{aligned} \quad (11)$$

Substituting the value of N_V in eq. (11) we get.

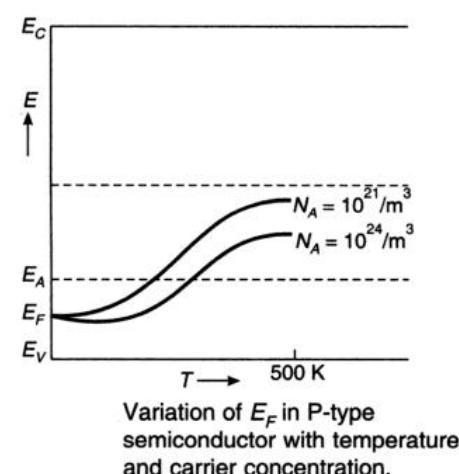
$$p = (2N_A)^{1/2} \left[\frac{2\pi m_h^* KT}{h^2} \right]^{3/4} \exp \left[\frac{E_V - E_A}{2KT} \right]$$

The above eq. represents the concentration of carriers in a *p-type* semiconductor.

VARIATION OF FERMI LEVEL WITH TEMPERATURE AND CONCENTRATION

p-type SEMICONDUCTOR

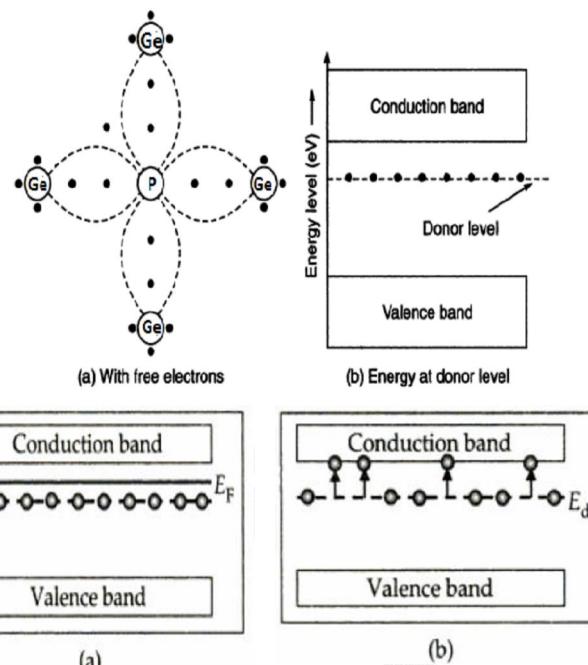
- ✓ At $T = 0 K$, the Fermi energy level lies at the middle of the VB and the acceptor level.
- ✓ At very high temperatures, it lies at middle of the energy gap. It shows that at very high temperature, the *p-type* material behave as an intrinsic material.
- ✓ As the acceptor concentration is increased the increase in Fermi energy is minimized and hence the Fermi level is moves down.



N-TYPE SEMICONDUCTOR:

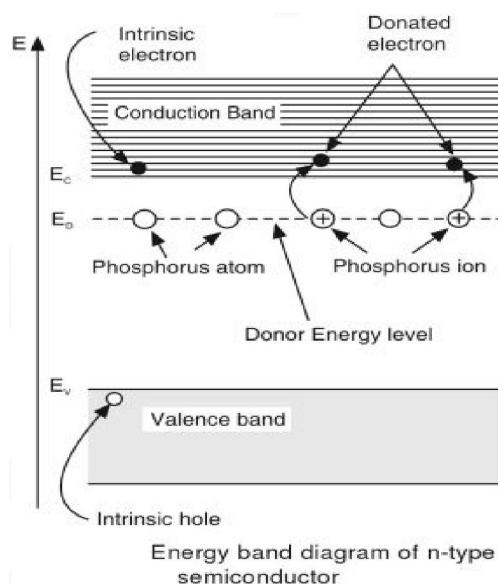
Generally pure semiconductors has **four** valence electrons and can form **four** covalent bonds. When a penta valent impurity, like **P** or **Antimony(Sb)**,(which have five valence electrons) is added to any Ge, the **four** electrons of Ge bond with 4 electrons of 'P' and one extra electron is left out alone. That, it is ready to '**donate**' this electron. Such type of semiconductor is called '**N-type semiconductor**' or '**DONOR**'.

In a N - type semiconductor holes are minority current carriers and electrons are majority current carriers. In a N- type semiconductor, the energy level of this donor impurity lies just *below* the conduction band of the semiconductor. This energy level is called **donor level** and it is represented as E_D .



(a) $T = 0 \text{ K}$ and (b) $T > 0 \text{ K}$

CARRIER CONCENTRATION IN N - TYPE SEMICONDUCTOR:



In **n - type** semiconductor, there is no acceptor atoms (*and hence the acceptor ions*), so acceptor ions ($N_A^- = 0$) are negligible . Further in **n - type** semiconductors, holes are due to thermal generation only, therefore '**p**' will be very small in comparison to N_D^+ , so we can write the charge neutrality equation for the **n - type** semiconductor as

$$n = N_D^+ \quad (1)$$

Where $n \rightarrow$ concentration of free electrons

$$n \rightarrow N_C \exp\left(\frac{E_F - E_C}{kT}\right)$$

$N_D^+ \rightarrow$ concentration of donor ions .

Concentration of donor ions N_D^+ is equal to the product of concentration of donor atoms N_D and the probability of the absence of electrons in the donor level E_D .

$$N_D^+ = N_D [1 - f(E_D)] \quad (2)$$

$$1 - f(E_D) = 1 - \frac{1}{1 + \exp\left(\frac{E_D - E_F}{KT}\right)} = \frac{\exp\left(\frac{E_D - E_F}{KT}\right)}{1 + \exp\left(\frac{E_D - E_F}{KT}\right)}$$

Since, $E_D < E_F$, $\exp\left(\frac{E_D - E_F}{KT}\right) < 1$ and hence the term $\exp\left(\frac{E_D - E_F}{KT}\right)$ in the denominator is negligible.

$$1 - f(E_D) = \exp\left(\frac{E_D - E_F}{KT}\right) \quad (3)$$

Sub eq. (3) in eq. (2)

$$\boxed{N_D^+ = N_D \exp\left(\frac{E_D - E_F}{KT}\right)}$$

Substitute n and N_D^+ values in eq. (1)

$$N_C \exp\left(\frac{E_F - E_C}{KT}\right) = N_D \exp\left(\frac{E_D - E_F}{KT}\right)$$

$$\begin{aligned} \text{i.e., } \frac{N_C}{N_D} &= \exp\left(\frac{E_C - E_F}{KT}\right) \exp\left(\frac{E_D - E_F}{KT}\right) \\ &= \exp\left(\frac{-2E_F + E_C + E_D}{KT}\right) \end{aligned} \quad (4)$$

Taking **log** on both sides of eq. (4) we get

$$\frac{-2E_F + E_C + E_D}{KT} = \log\left(\frac{N_C}{N_D}\right)$$

$$E_F = \frac{E_C + E_D}{2} - \frac{KT}{2} \log\left(\frac{N_C}{N_D}\right) \quad (5)$$

Eq. (5) gives the equation for the Fermi level in an *n-type semiconductor*.

The concentration of electron in the conduction band is

$$n = N_C \exp\left(\frac{E_F - E_C}{KT}\right) \quad (6)$$

Sub eq. (5) in eq. (6)

$$n = N_C \exp\left(\frac{E_C + E_D}{2KT} - \frac{E_C}{KT} - \frac{1}{2} \log \frac{N_C}{N_D}\right)$$

$$= N_C \exp\left(\frac{E_C + E_D}{2KT}\right) \left(\frac{N_D}{N_C}\right)^{1/2}$$

$$n = (N_C N_D)^{1/2} \exp\left(\frac{E_C + E_D}{2KT}\right) \quad (7)$$

Substituting the value of $N_C = 2 \left[\frac{2\pi m_e^* KT}{h^2} \right]^{3/2}$ in the eq. (7)

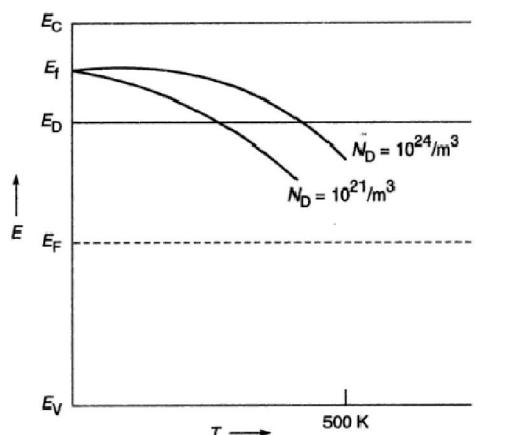
$$\boxed{n = (2N_D)^{1/2} \left[\frac{2\pi m_e^* KT}{h^2} \right]^{3/4} \exp\left[\frac{E_D - E_C}{2KT}\right]} \quad (8)$$

Eq. (8) gives the carrier concentration of electron in an *n-type semiconductor material*.

VARIATION OF FERMI LEVEL WITH TEMPERATURE AND CONCENTRATION

n – type SEMICONDUCTOR

- ✓ At **0 K** the Fermi level lies in between the conduction band and the donor level.
- ✓ As the temperature increases from **0K**, the Fermi level falls.
- ✓ At higher temperature, it falls below the donor level and hence, it approaches the centre of the forbidden gap. It shows that the material behaving as an intrinsic semiconductor.
- ✓ As the donor concentration is increased, the Fermi level will move up.



Variation of fermi level in an n-type semiconductor with temperature

DIRECT AND INDIRECT BAND GAP SEMICONDUCTORS:

According to the band theory of solids, the energy spectrum of electrons consists of a large number of energy bands and are separated by forbidden regions. The band gap is the difference in the energy between the lowest point of conduction band and highest point of valence band.

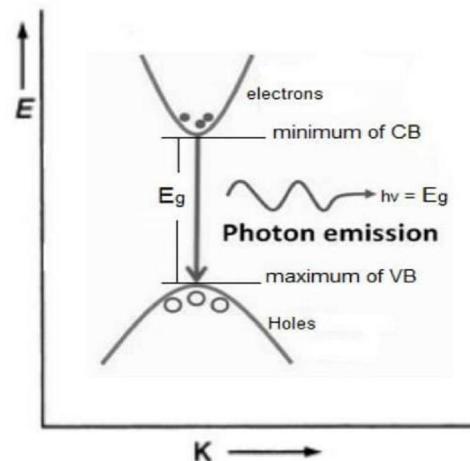
Based on the structure of energy bands and type of energy emission, semiconductors are classified into two types.

- *Direct band gap semi conductor*
- *Indirect band gap semiconductor*

DIRECT BAND GAP SEMICONDUCTOR:

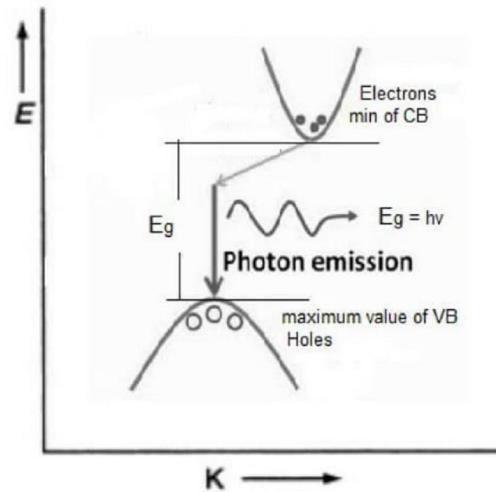
- ✓ The maximum of **VB** and the minimum of **CB** exists at the same value of wave number (K). Such semiconductors are called **direct band gap semiconductor**.
- ✓ In this type during the recombination of holes and electron, a **photon of light** is released. This process is known as **radiative recombination**. Also called as **spontaneous emission**.
- ✓ It is more effective, because the direction of motion of electron remains unchanged.
- ✓ In this type of semiconductors life time(*i.e., recombination time*) of charge carrier is very less.
- ✓ Electron – hole pair can be easily generated because it requires less momentum.
- ✓ Recombination probability is much high.
- ✓ These are used to fabricate LEDs and laser diodes.
- ✓ These are mostly from the compound semiconductors.

Ex: InP, GaAs



INDIRECT BAND GAP SEMICONDUCTOR:

- ✓ The maximum value of **VB** and the minimum value of **CB** exists at the different values of wave number (K). Such semiconductors are called **Indirect Band Gap Semiconductor**.
 - ✓ In this type, **heat energy** is produced during the recombination of holes and electrons. This process is known as **non radiative** recombination.
 - ✓ It is less efficient, because the direction of motion of electron changed.
 - ✓ In this type of semiconductors life time (*i.e., recombination time*) of charge carrier is high.
 - ✓ The incident process is slower, because it requires an electron, hole and phonon for interaction.
 - ✓ Recombination occurs through some defect states.
 - ✓ Due to the longer life time of charge carriers, these are used to amplify the signals as in the case of diodes and transistors.
 - ✓ These are mostly from the elemental semiconductors.
- Ex:** Si(0.7 eV), Ge(1.12 eV).



CARRIER TRANSPORT

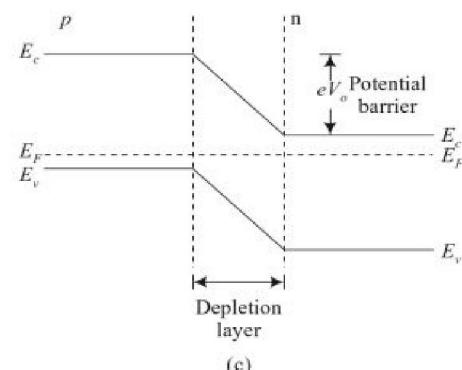
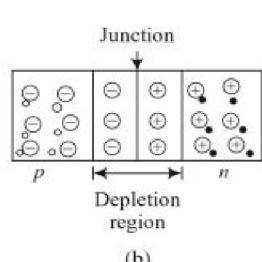
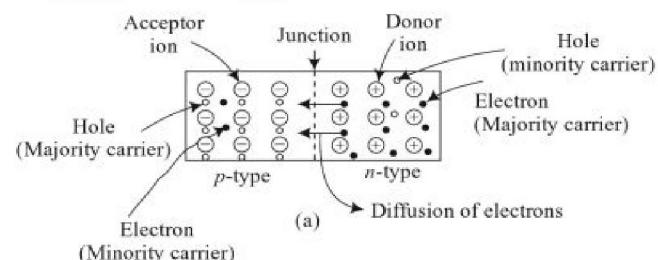
DIFFUSION CURRENT: The current that flows across the junction of a diode due to the difference in the concentration of holes or conduction electrons on its either side is called diffusion current.

DRIFT CURRENT: The current that flows through the diode due to the electric field is called drift current.

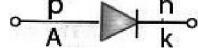
JUNCTION DIODE:

Diode is a device with two electrodes (*di* means two and *-ode* means electrode).

Formation of p – n Junction diode:



p-n junction diode without biasing (a) When p-type and n-type are brought in contact (b) Depletion region in p-n junction (c) Energy band diagram

- ✓ When a p – type semiconductor is suitably joined with n – type semiconductor a p – n junction diode is formed and the symbol of the p – n junction diode is 
- ✓ Because of the contact, some of the electrons from n – side enter into p - side and holes from p – side goes to n – side.
- ✓ At junction the electrons and hole combine and neutralize each other.
- ✓ Later in the region close to the junction only negative ions are left behind on p – side and only positive ions on n – side.
- ✓ As a result a narrow charged region on either side of the junction is formed where there are no mobile charge carriers.
- ✓ Since this region is depleted of mobile charge carriers it is called ***depletion region or charge free region or space charge region or transition region.***
- ✓ The thickness of this region is usually in the order of $0.5 \mu m$ or 10^{-6} to $10^{-7} m$.
- ✓ The depletion layer contains positive and negative immobile ions on either side of the p – n junction. These ions set up a potential difference across the p – n junction which opposes the further diffusion of electrons and holes through the junction. This potential difference is called ‘Potential barrier’.

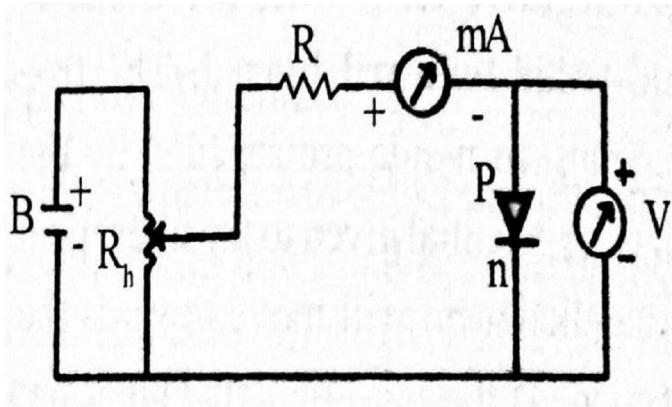
The potential barrier is about **0.7 V** for ‘Si’ and **0.38 V** for ‘Ge’ at room temperature.

USES:

1. It is used as an electronic switch.
2. In a rectifier circuit, it is used to convert *a.c to d.c*
3. Certain p – n diodes glow on supply of electricity.

I – V CHARACTERISTICS:

Semiconductor diode is connected to a battery through a rheostat R_h . A ‘mA’ is connected in series to the diode to measure current (I) and a voltmeter is connected across the diode to measure the voltage (V). The diode is forward biased and by varying the voltage across the diode, the current is measured. The polarity of diode is reversed so that it gets reverse biased and **mA** is replaced with micro ammeter **μA** . The voltage across the diode is varied and the corresponding current is measured.

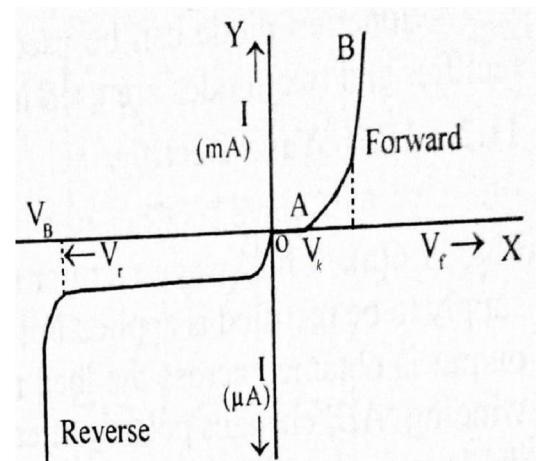


FORWARD BIAS CHARACTERISTICS:

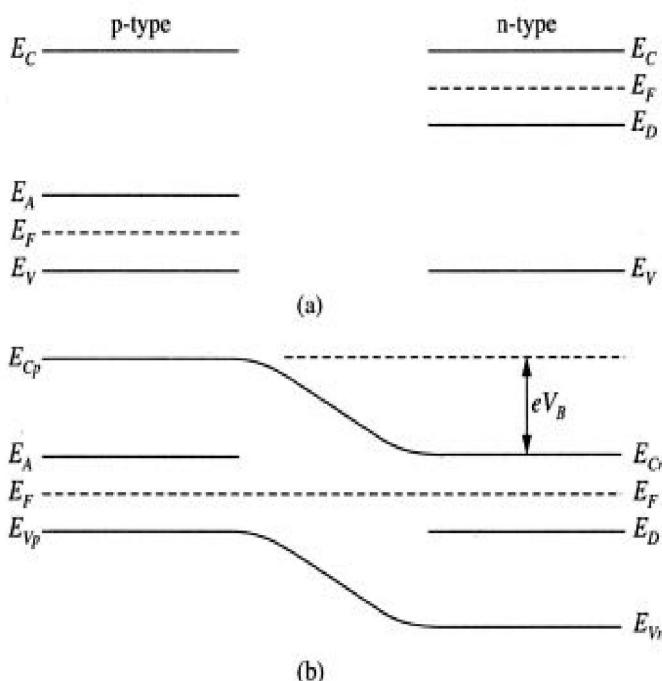
When the battery voltage is zero diode does not conduct and current is zero. As the forward battery voltage increases, the barrier potential starts decreasing and a small current begins to flow. The forward current increases slowly at first but as soon as the battery voltage increases, the forward current increases rapidly. The battery voltage at which the forward current starts increasing rapidly is known as ‘**knee voltage V_K or threshold or cut in or offset voltage**’. The value of cut in voltage for **Ge** is around **0.2 V** to **0.3 V** and for **Si** it is around **0.6 V** to **0.7 V**. If the voltage is increased beyond threshold voltage, the forward current increase exponentially and large current flows.

REVERSE BIAS CHARACTERISTICS:

In the reverse bias, small current flows in the circuit due to minority charge carriers. The applied reverse voltage appears as forward bias to these minority charge carriers. Therefore a small current flows in the reverse direction. This current is called reverse saturation current. If the reverse voltage is increased further after some voltage, there will be a sudden rise of reverse current. This region is named as ***break down region***.



ENERGY LEVEL DIAGRAMS OF p – n JUNCTION DIODE:



(a) Energy levels in p-and n-type semiconductors before contact (b) Energy levels in the junction after p-and n-type semiconductors are put in contact.

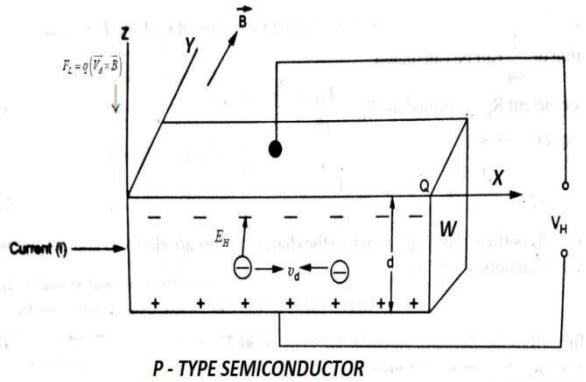
HALL EXPERIMENT:

When magnetic field is applied perpendicular to a current carrying conductor (metal or semiconductor) then a voltage is developed in the material perpendicular to both magnetic field and current in the conductor. This effect is known as ***Hall effect*** and the voltage is developed is known as ***Hall voltage* (V_H)**.

Explanation:

Consider a rectangular block of extrinsic semiconductor. Let a current ' i ' is passed in the conductor along ***X – direction*** and magnetic field (\vec{B}) is established along ***Y – direction***, then the charge carrier experience a Lorentz force (F_L) along the ***Z – direction***. The direction of this force is noted by Fleming left hand rule. As a result of this force (downward), the charge carriers are forced down into the bottom surface.

If the specimen is a **P-type semiconductor**, Since the holes are the charge carriers, they are forced down into the bottom surface and hence the upper surface is occupied by the electrons. Therefore, a potential difference is developed between the upper and bottom surface. This Hall potential V_H can be measured by connecting two surfaces to a voltmeter.



This separation of charge carriers creates an electric field (E_H) in the upward direction (*positive z-direction*).

These charge carriers are moving in a magnetic field in the semiconductor, they experience Lorentz force

$$\begin{aligned} F_L &= q(\vec{V}_d \times \vec{B}) & (V_d = \text{drift velocity of the carriers}) \\ &= qV_d B \sin \theta, \\ &= qV_d B \sin 90^\circ \end{aligned}$$

($\theta = 90^\circ$ bcz force acting on charge perpendicularly)

$$= qV_d B \quad (q = e)$$

$$\boxed{F_L = eV_d B}$$

The electric force due to electric field created by the surface charges.

$$F_H = qE$$

$$\boxed{F_H = eE_H}$$

Where, E_H is the hall electrical field.

After some time both the forces become equal in magnitude and act in opposite direction, the situation is said to be under equilibrium.

At equilibrium, $F_H = F_L$

$$eE_H = eV_d B$$

Cancelling common terms , we get

$$E_H = V_d B \quad (1)$$

The current density is

$$J = neV_d \quad (2)$$

From eq. (2) and (3)

$$E_H = \frac{BJ}{ne} \quad (3)$$

The current density is also given by

$$J = \frac{I}{A} \quad (4)$$

From eq. (3) and (4)

$$E_H = \frac{BI}{neA} \quad (5)$$

If E_H be the Hall voltage in equilibrium, the Hall electrical field $E_H = \frac{V_H}{d}$

Substituting $E_H = \frac{V_H}{d}$ in equation (5)

$$\frac{V_H}{d} = \frac{BI}{neA} \quad (6)$$

Eq. (6) can be written by taking $\boxed{\mathbf{R}_H = \frac{1}{ne}}$ (where \mathbf{R}_H is the Hall coefficient) as

$$\frac{V_H}{d} = \frac{BI}{A} \mathbf{R}_H \quad (7)$$

By substituting $A = w \times d$ (Area of cross section = width \times thickness) in eq. (8)

$$\frac{V_H}{d} = \frac{BI}{wd} \mathbf{R}_H$$

Cancelling common terms, we get

$$V_H = \frac{BI}{w} \mathbf{R}_H \quad (8)$$

From eq. (8) the Hall coefficient is

$$\boxed{\mathbf{R}_H = \frac{V_H w}{BI}} \quad (9)$$

Eq. (9) gives the value of the \mathbf{R}_H by measuring I, B, w , and V_H the Hall coefficient is determined. From $\mathbf{R}_H = \frac{1}{ne}$ one can find the value of the concentration of the carriers.

By knowing the concentration of the carriers the mobility of the charge carriers is determined using the relation.

$$\sigma = ne\mu$$

$$\boxed{\mu = \mathbf{R}_H \sigma}$$

Where σ is the electrical conductivity of the material.

The above \mathbf{R}_H equations are derived by assuming that the velocity of the electron is constant. But due to thermal agitation the velocity of the electron is not a constant. It is randomly distributed. So, a correction factor $\left(\frac{3\pi}{8}\right)$ is introduced in the Hall coefficient. Therefore \mathbf{R}_H can be written as

$$\mathbf{R}_H = -\frac{3\pi}{8} \left(\frac{1}{ne} \right) \quad (\text{for } N\text{-type})$$

$$\mathbf{R}_H = \frac{3\pi}{8} \left(\frac{1}{pe} \right) \quad (\text{for } P\text{-type})$$

$$\boxed{\mathbf{R}_H = -\frac{1.18}{ne} = \frac{1.18}{pe}}$$

For ***N-type*** material, Since, the charge is negative, \mathbf{R}_H is also negative and for a ***P-type*** material, \mathbf{R}_H is positive.

Uses:

- ✓ It is used to find out whether the given semiconductor is N-type or P-type.
- ✓ It is used to measure carrier concentration, mobility and conductivity of a semiconducting material.
- ✓ Hall voltage is produced of two input quantities namely the current and the magnetic field. Using this principle, the Hall effect device is used as a multiplier.
- ✓ It is used as a magnetic field sensor. Using the Hall effect devices, the magnetic field ranging from **1 μ T** to **1T** is sensed.